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Electrothermal-Chemical Plasma Ignition of Gun-Propelling Charges: The Effect of Pulse Length

by Lang-Mann Chang and Stephen L. Howard

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14. ABSTRACT
An experimental investigation was conducted on the effect of plasma pulse length on gun-charge ignition. The investigation began with visualization of open-air, capillary-generated plasma jet flows and concluded with plasma interaction with a JA2 propelling charge in a 25-mm gun chamber. The plasma energy utilized by the capillary was about 1.1 kJ. With plasma pulse lengths of 0.3 and 1 ms, the resultant flow fields observed were profoundly different in several areas of importance. Typically, the longer pulse length produced a narrower flow field with a greater penetration into the air. The luminosity in the flow region also remained much longer, although at lower intensity. In a JA2-packed chamber, the overall luminosity was higher with the 0.3-ms pulse length during the early time; however, ignition/combustion of the propellant was not sustained. With the 1-ms pulse length, at the same level of energy input from the capillary, sustained ignition/combustion was achieved. Results conclude that plasma pulse length is of importance in optimizing a plasma ignition system for effective ignition of a charge system using a minimum amount of plasma energy.

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1. Introduction

Results of previous experimental studies and computer modeling (*1–7*) have ascertained the potential of electrothermal-chemical (ETC) plasma ignition to offer many benefits over conventional igniters for ignition of advanced charge systems. As contrasted with the hot gases and condensed phase material venting from a conventional igniter, plasma can more rapidly propagate into a propellant bed and interact directly with more propellant material by virtue of its high mobility as a result of low molecular weight. This advantage is significant in achieving uniform ignition throughout a densely-packed propellant charge. Experimental results (*7*) also reveal evidence of in-depth (subsurface) grain changes for some propellant formulations as a result of radiative heat transfer from the plasma or heat transfer to the propellant by deposition of metallic vapor (*8, 9*) from the plasma. The metallic vapor is produced from the exploding wire and erosion of the electrodes in the capillary. The nozzle at the exit end of the capillary also may be eroded and thus produce hot metallic vapor. The subsurface grain changes are generally believed to be a key factor contributing to the augmentation of the propellant burn rate observed. Together with its high temperature (15,000 K or higher) property, plasma may achieve rapid ignition and augmentation of combustion processes for difficult-to-ignite, insensitive propellant charges. Furthermore, a plasma igniter capable of modulating the amount of electrical energy input to the charge system may offer the potential of compensating for the temperature-dependent burning characteristics inherent in solid propellant.

In recent years, many studies (*10–18*) have been conducted in an effort of characterizing plasma properties, plasma jet flows, and interactions with propellant under ambient conditions in the open air or in a closed empty chamber. These studies have provided considerable understanding of the characteristics of capillary-generated plasmas, species, flow patterns, heat-transfer mechanisms, and changes of propellant properties. However, there are other critical areas remaining to be investigated, such as the flow dynamics in a charge system under actual gun firing environments. Typically, the plasma propagation in the propellant bed, the initiation of propellant ignition, and the subsequent combustion processes are important in guiding charge designs as well as being used for validation of modeling results. Early experiments (*19*) with a 25-mm closed chamber packed with inert propellant discs (a stack of concentric discs with a center hole) revealed possible occurrence of several undesired hot regions along the propellant bed when subjected to plasma energy input (see figures 1 and 2). These hot regions may have an adverse effect on ballistic performance and operational safety.

The present experiments incorporate a new power supply capable of delivering energy up to 3 kJ. In addition, an inductor can be added to the electrical system to increase the nominal plasma pulse length from 0.3 ms to about 1 ms. Thus, this power supply unit enables further examination of effects of variable plasma energy and variable plasma pulse lengths.

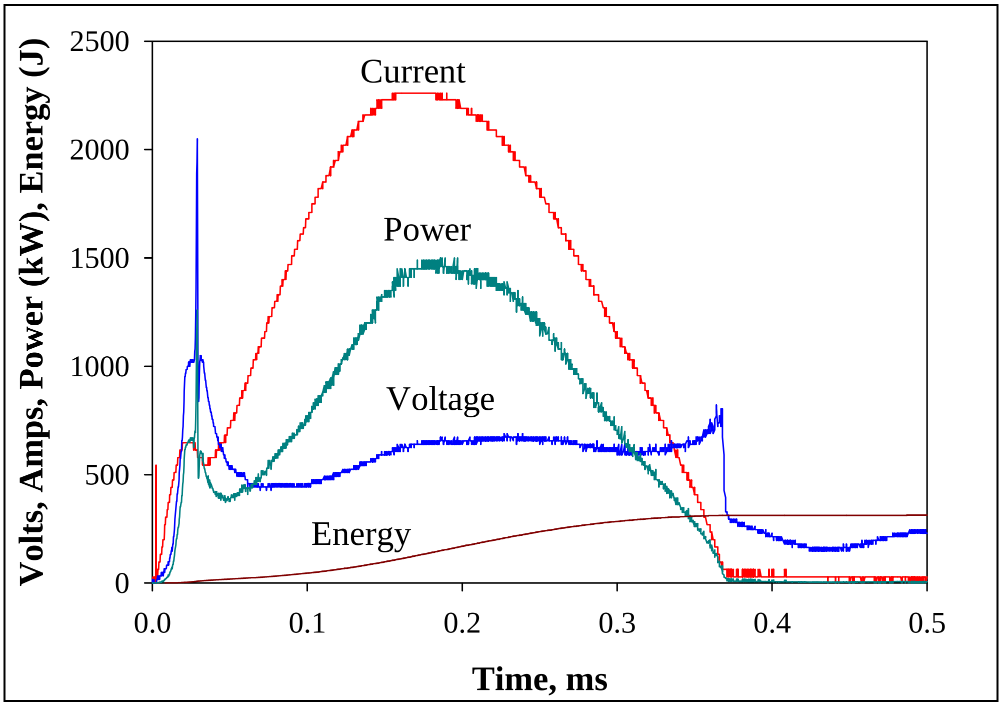

Figure 1. Typical plasma capillary output.

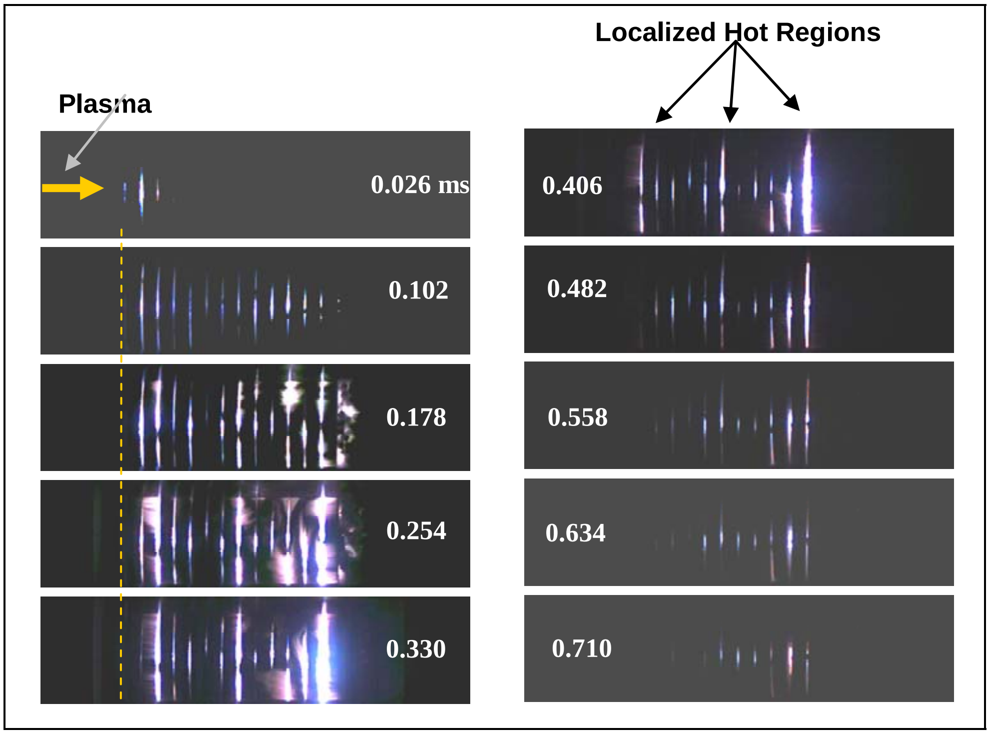

Figure 2. Capillary output and plasma flow in 25-mm closed chamber packed with inert discs (gap width of 0.5 mm between discs).

Since a change of pulse length might well influence the plasma flow characteristics, a significant part of the current effort was devoted to comparing the open-air plasma jet flow fields resulting from the two different pulse lengths. Subsequently, experiments with live propellant were conducted to characterize the flow interaction with JA2 disc propellant in a 25-mm closed chamber.

2. Experimental

In this study, an ablative capillary was used to generate plasma. As described elsewhere (*19*), it basically consisted of a stainless-steel cylinder that housed a polyethylene tube with an outside diameter of 9.5 mm and an inside diameter of 3.2 mm. In the tube was a 0.1-mm nickel wire fuse which had extensively been used as an exploding wire in the past (*3*). The electrodes at the ends of the tube were made of tungsten at one end (anode) and stainless steel at the other end (cathode). The length of the capillary tube was adjustable giving a length-to-diameter ratio of 12–22. It was determined that the ratio of 16 would deliver energy efficiently for the present experimental system. The pulse power supply used was capable of delivering variable amounts of energy up to 3 kJ with an upper voltage limit of ~3 kV.

A Phantom V5 high-speed digital camera was used for high-speed photography of plasma flows in all experiments. The camera can record events at a frame rate up to 64,000 pictures per second. In present experiments, a frame rate between 13,000 and 20,000 pictures per second was adequate for capturing details of the flow field with good resolution. A neutral density optical filter placed in front of the camera lens was necessary to reduce the light intensity to a level that the shock waves inside the plasma jet could be visualized.

Figure 3 shows the apparatus designed for the experiments with a disc propellant bed. Basically, it simulated the combustion chamber of the 25-mm cannon. The apparatus has been described elsewhere and only its cogent details are presented here (*18*, *20*). The chamber was fabricated from an optically clear acrylic tube, allowing cinematography of the plasma flows and the ignition/combustion events occurring in the charge. The chamber could withstand pressures higher than 7 MPa before rupture, depending upon the pressurization rate in the chamber. The capillary plasma injector was mounted at the breech end of the chamber. Up to three Kistler pressure transducers (Model 211B1) were installed in the chamber wall for monitoring chamber pressures at the ends of the chamber. The voltage, current, chamber pressures, and flame propagation were recorded directly. Using the measured voltage and current, the power and energy output of the capillary were calculated.

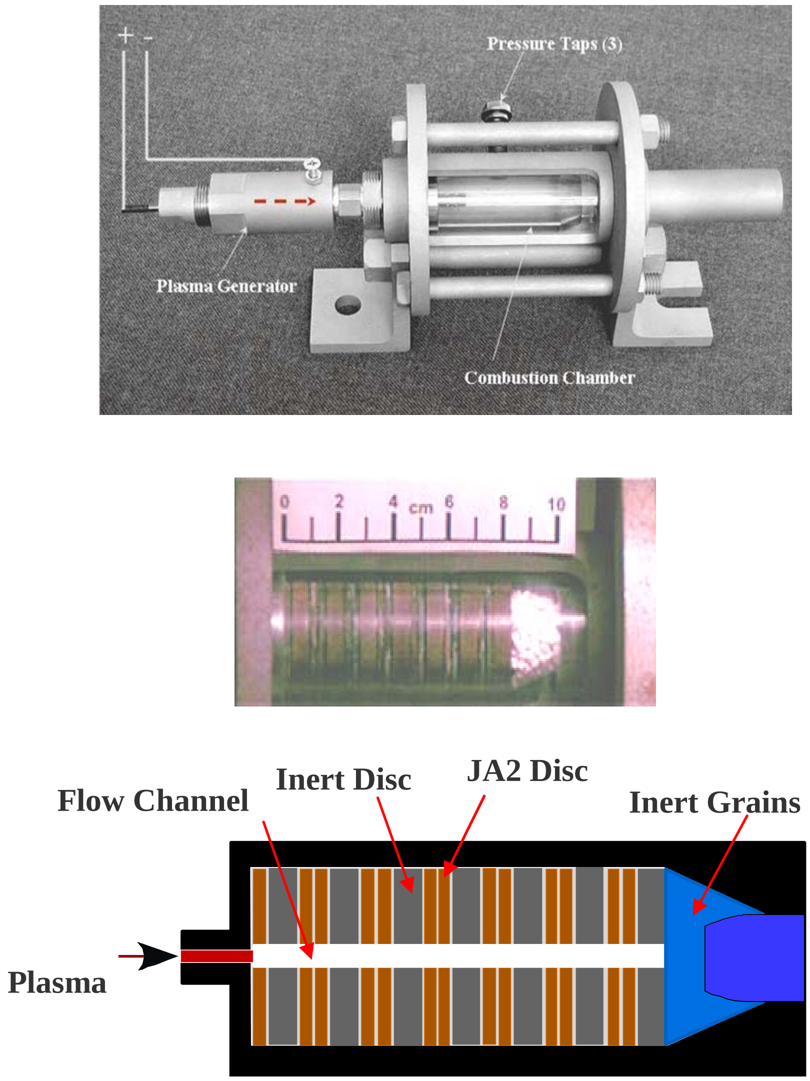

Figure 3. Photo of disk propellant bed apparatus at top, close-up photo of chamber with live JA2 disks alternating with inert disks (gap width of 0.5 mm) in center, and schematic at bottom.

3. Results and Discussion

3.1 Plasma Jet Flows in Open Air

Open-air tests provide an opportunity of direct visualization of an undisturbed flow field effusing from a capillary. The data obtained can be very useful in helping understand the complex flow phenomena occurring in a propellant bed. As previously mentioned, the plasma pulse length

could be an important variable that influences the flow field. The following presents the results for two plasma pulse lengths, 0.3 and 1 ms.

3.1.1 Pulse Length of 0.3 ms

Figure 4 exhibits the power and energy output from the capillary calculated based on the voltage and current measured directly in a particular experimental run. The first voltage spike occurred when the nickel fuze in the capillary tube started breaking up and the second spike (the largest, 3.25 kV) occurred when the wire had exploded almost completely. Following was the generation of highly conductive plasma gases that connected the electrodes at the two ends of the capillary tube and completed the electrical circuit. The voltage remained somewhat constant while the plasma completed the circuit and the current flowed.

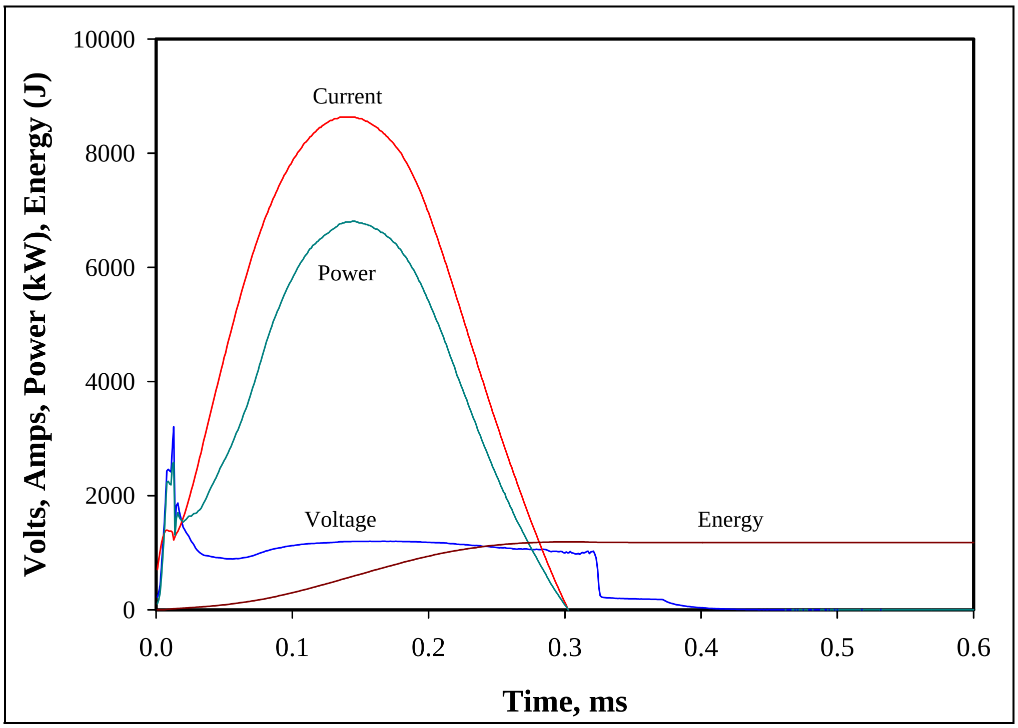

Figure 4. Plasma capillary output (pulse length of 0.3 ms).

Figure 5 presents a series of photos showing a side view of the plasma jet effused from a capillary having a flow diameter of 3.2 mm at the exit. Through the use of a neutral-density optical filter, the shock structure inside the flow field became visible. There were multiple concentric barrel shocks that developed in front of the capillary. The appearance of more than a single barrel shock seemed unusual. If not an inherent flow phenomenon, it could have been induced by an imperfect flow channel wall condition. In the present setup, a steel nozzle (6.4 mm long with a 3.2-mm inside diameter) was connected to the polyethylene tube capillary (which also had an inside diameter of 3.2 mm). A slight misalignment between these two parts might exist due to the fact that the polyethylene tube was not perfectly round.

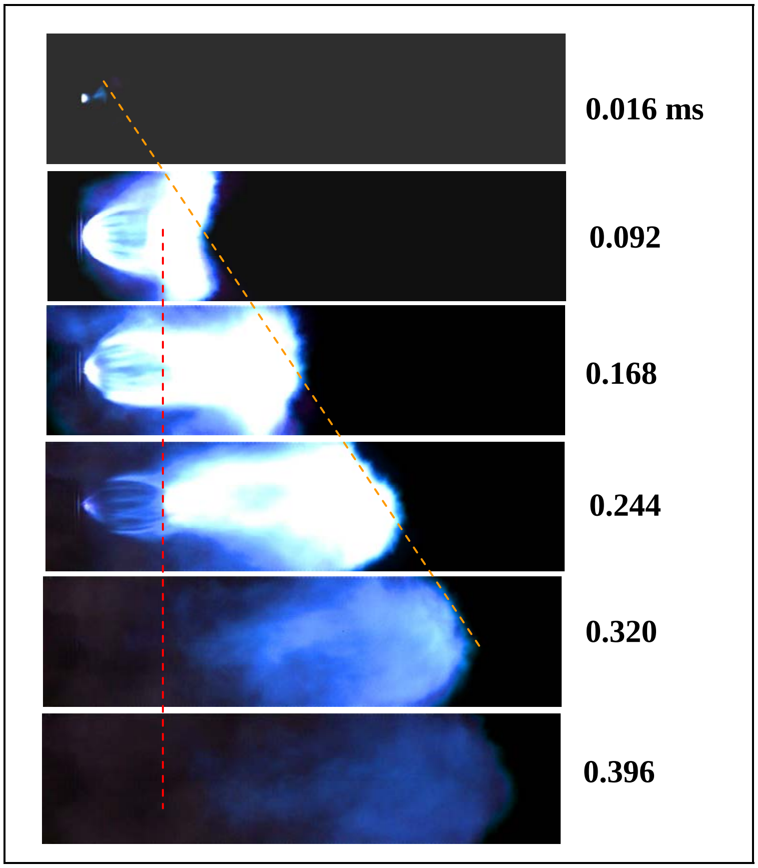

Figure 5. Plasma jet flow in open air with a pulse length of 0.3 ms (dotted lines show location of Mach disk and luminous zone front from frame to frame).

At the forward end of the barrel shocks was a Mach disc at which the light intensity was very high, through which the flow returned to subsonic speeds. Once the barrel shocks had established, the Mach disc seemed to stay at a distance nearly constant from the capillary exit throughout most of the flow time-history. In this particular flow, the distance was measured to be ~25 mm. In front of the Mach disc, another distinct supersonic flow region was developed and it finally terminated with a precursor shock. The light intensity was very high in the region between the Mach disc and the precursor shock.

3.1.2 Pulse Length of 1 ms

Figure 6 shows the resultant electrical parameters of the capillary when the pulse length was extended to 1 ms (at an energy output comparable to the system with a pulse length of 0.3 ms). With this one change, figure 7 shows a flow field profoundly different from the one shown in figure 5. The flow region became narrower, but much longer. The Mach disc also stayed at a nearly fixed distance from the capillary exit, ~18 mm in this test. Similarly, the light intensity was very high in the region in front of the Mach disc. In fact, in another experiment using a denser optical filter, a series of unconnected bright regions appeared in front of the Mach disc.

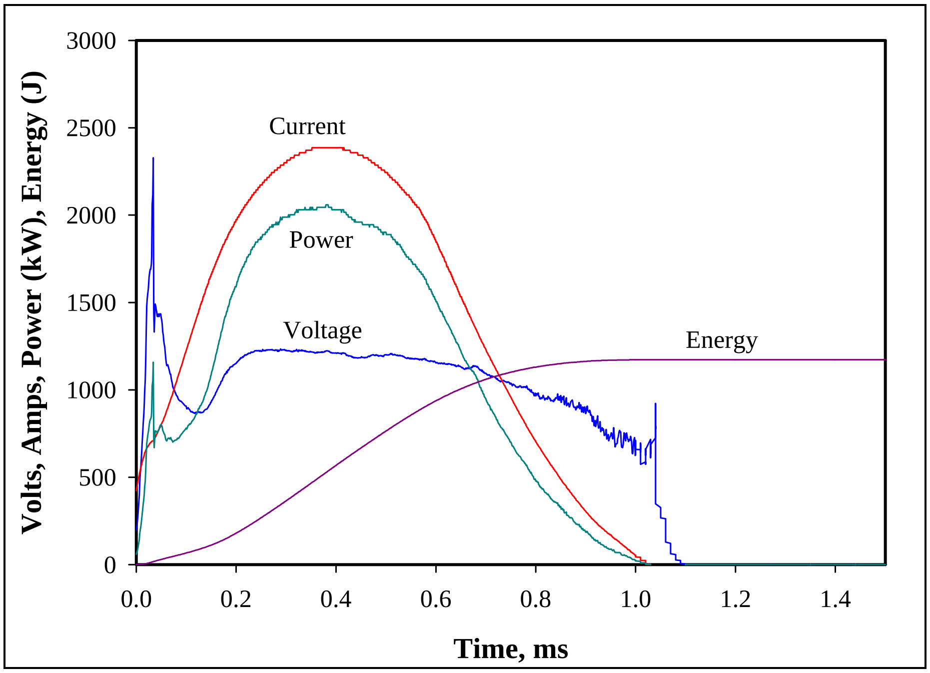

Figure 6. Plasma capillary output (pulse length of 1 ms).

The increased depth of flow penetration, coupled with a prolonged flow time, could have a favorable result in achieving effective and uniform ignition of a propelling charge.

It is of interest to examine the propagation speed of the luminous zone. Using the photographic data given in figures 5 and 7, the distance of the front edge of the luminous zone from the capillary exit at a given time can be measured. The result is plotted in figure 8, showing that a linear relationship can be approximated for the front edge location versus time for most of the flow time-history. Based on this approximated linearity, the propagation speed of the luminous zone in the axial direction was estimated to be 372 m/s, which is slightly higher than the sound speed in air at atmospheric temperature and pressure, 344 m/s.

3.2 Plasma Flow in a 25-mm Disc Propellant Charge

In this test series, two rounds were fired with JA2 disc propellant packed in a 25-mm gun simulator chamber, one with a plasma pulse length 0.3 ms and the other with a pulse length of 1 ms. The gap width between adjacent JA2 discs was 0.5 mm in both rounds, and was uniform along the propellant bed.

The electrical parameters from a live propellant shot with a pulse length of 0.3 ms are displayed in figure 9. The corresponding pressure-time history displayed in figure 10 was obtained at the rear end (breech end) of the chamber. It shows a sharp rise during the plasma capillary output period. The pressure then started falling immediately near the end of the plasma output at 0.3 ms (pulse length noted in figure by dashed line). The pressure rose again at about 0.7 ms until 0.82 ms.

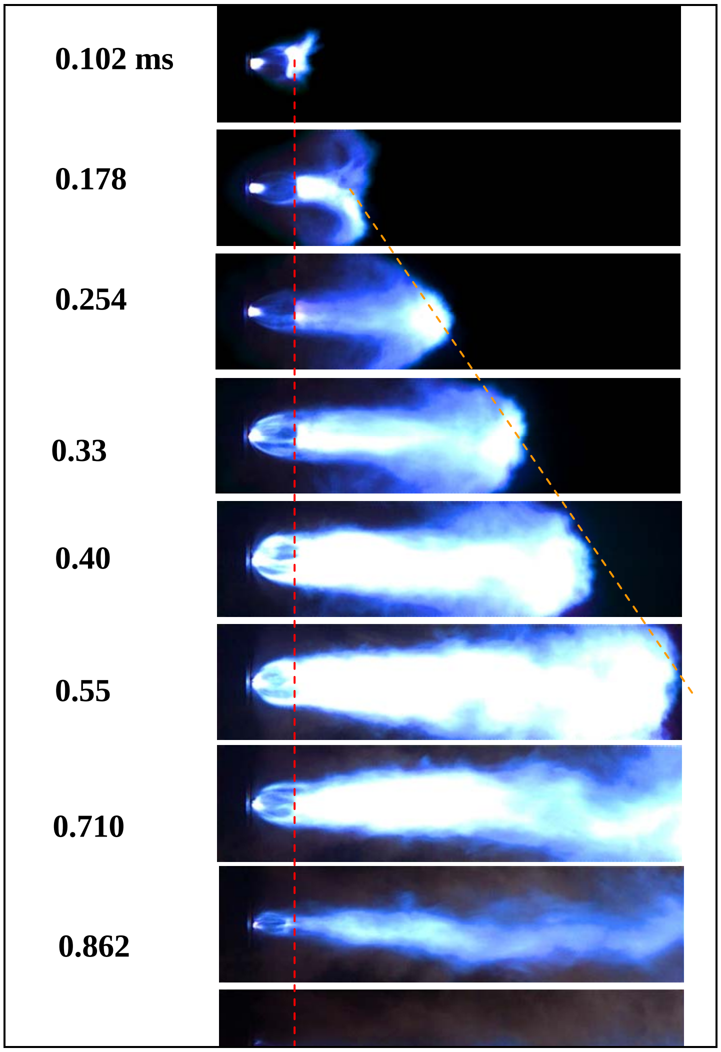

Figure 7. Plasma jet flow in open air with a pulse length of 1 ms (dotted lines show position of Mach disk and luminous zone front from frame to frame).

This pressure rise must have resulted from ignition of the propellant. However, the ignition/combustion was unable to sustain and the pressure gradually decreased to zero. The inability of sustained ignition/combustion could be explained as follows. When the high-speed plasma entered the propellant bed, pyrolysis occurred on the propellant surfaces which were subjected to direct plasma flow impingement. The pyrolysis products from the surfaces were immediately removed and blown into the relatively cool regions in the down stream. Due to a lack of continued supply of heat as a result of the short pulse time, ignition/combustion was unable to sustain. This phenomenon has been reported previously (*21*). Also note that high-amplitude pressure oscillations were present in the chamber, induced by the complex interaction of plasma shock wave flow with solid boundaries, such as propellant discs in particular. The chamber remained intact in this test.

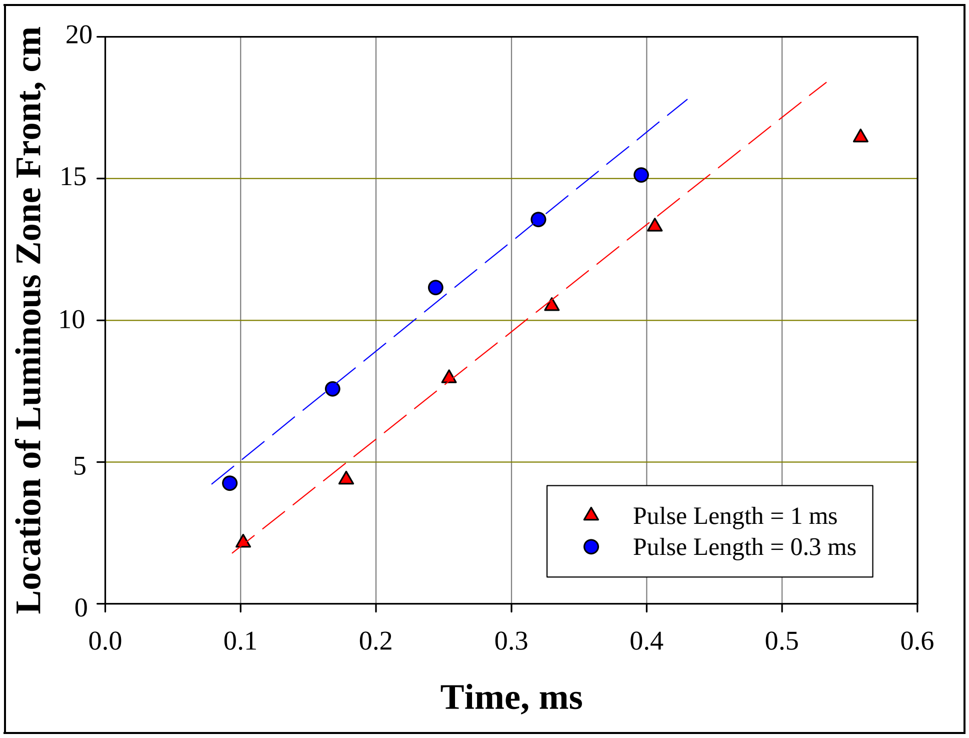

Figure 8. Front-edge location of luminous zone as a function of time.

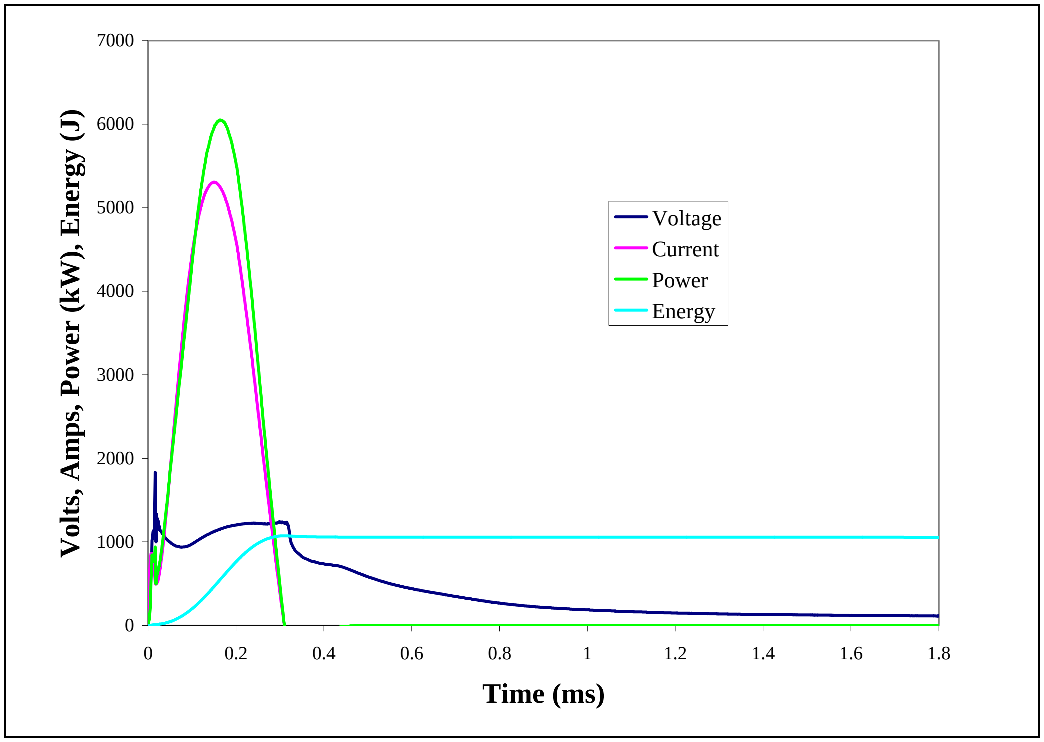

Figure 9. Electrical parameters measured for a live propellant shot with a pulse length of 0.3 ms.

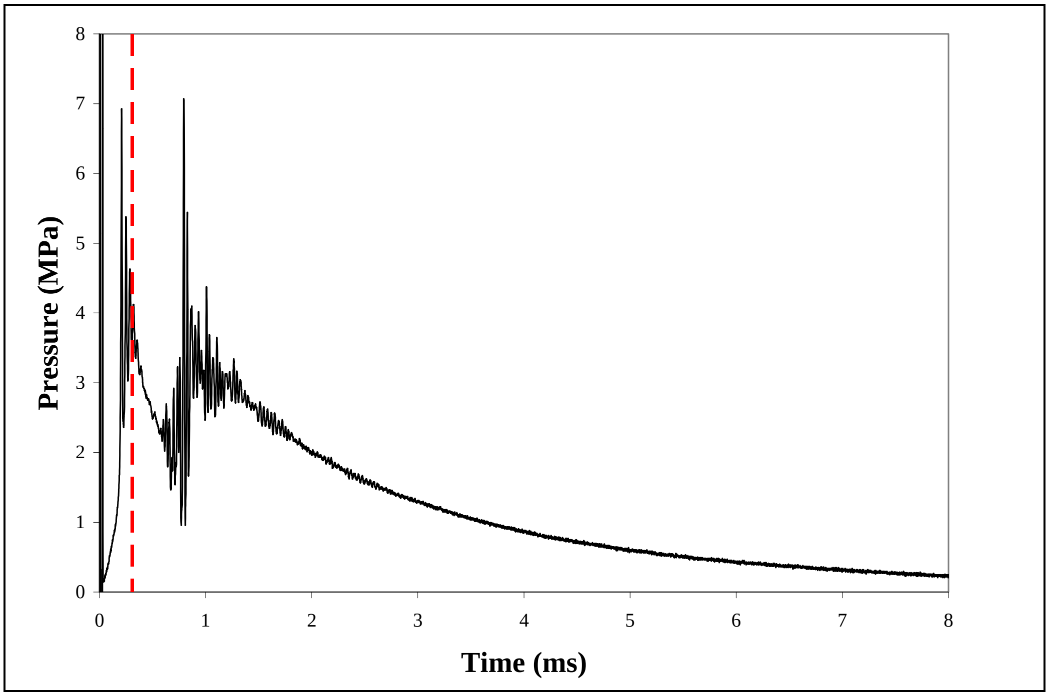

Figure 10. Pressure-time history at breech end for live propellant shot in figure 9 (dashed line indicates end of electrical pulse).

The first frame of the high-speed video in figure 11 shows what the propellant bed looked like before injection of the plasma. The bed was filled from the breech end with ~8 cm of alternating inert and live JA2 disks with a gap width of 0.5 mm between disks. The chambrage region from 8 to 10 cm was filled with inert granular propellant (white region in first frame of figure 11).

As the plasma from the 0.3-ms pulse filled the propellant bed, the progression of the high-intensity light was readily visible through the gaps between the propellant. After the plasma injection stopped, the intensity of light quickly diminished over the majority of the bed length. However, there were some localized regions where light persisted (most notably near the end of the central core channel next to the chambrage region where the plasma flow would have stagnated) to some extent for a few milliseconds. In the end, all traces of light and flame were extinguished.

Using the same capillary but with an extended electrical pulse length of 1 ms (electrical parameters shown in figure 12 and pressures observed at the breech shown in figure 13), figure 14 shows that the overall light intensity was reduced to some extent along the propellant bed, though the energy level of the discharge was nearly the same (a little over 1 kJ of discharged energy). Furthermore, the high-intensity light appeared at a much later time period—after 0.1 ms as opposed to 0.04 ms (see figure 11). However, the high-intensity light was present about two times longer in duration. This longer duration gave a longer heating time for the propellant and thus might have helped ignite it. Comparing figures 10 and 13 shows that the pressures generated during the

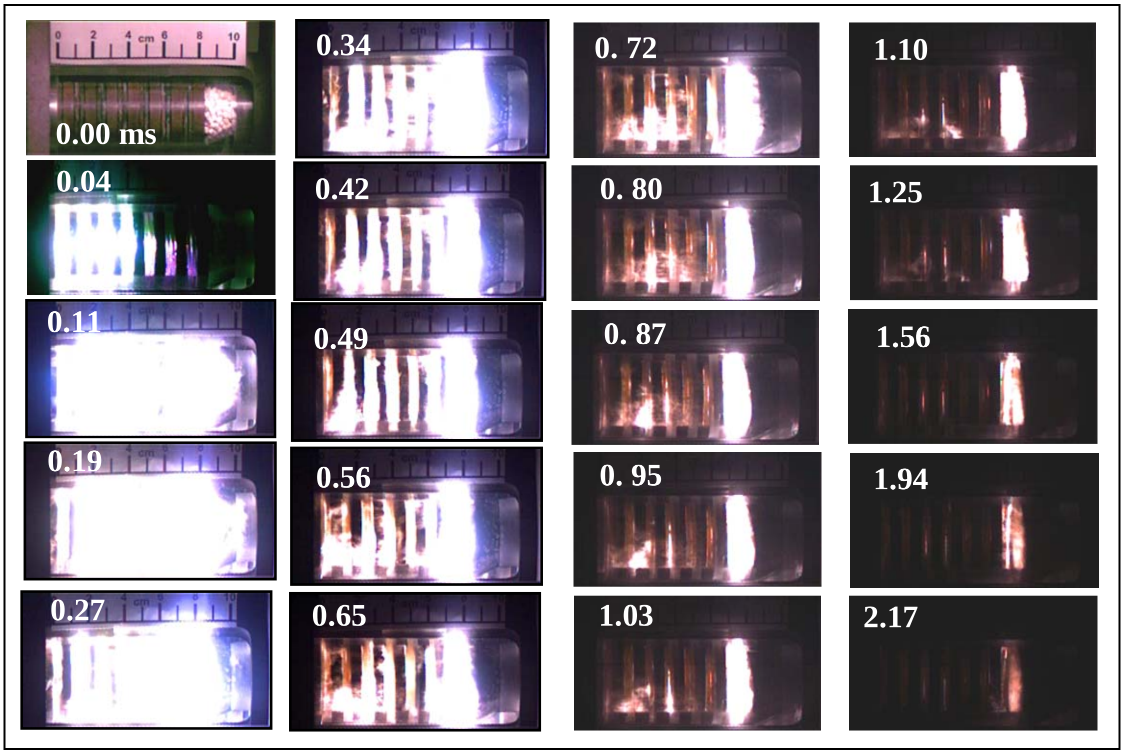

Figure 11. High-speed video of flamespread in a 25-mm live-JA2 propellant bed ignited with a pulse length of 0.3 ms.

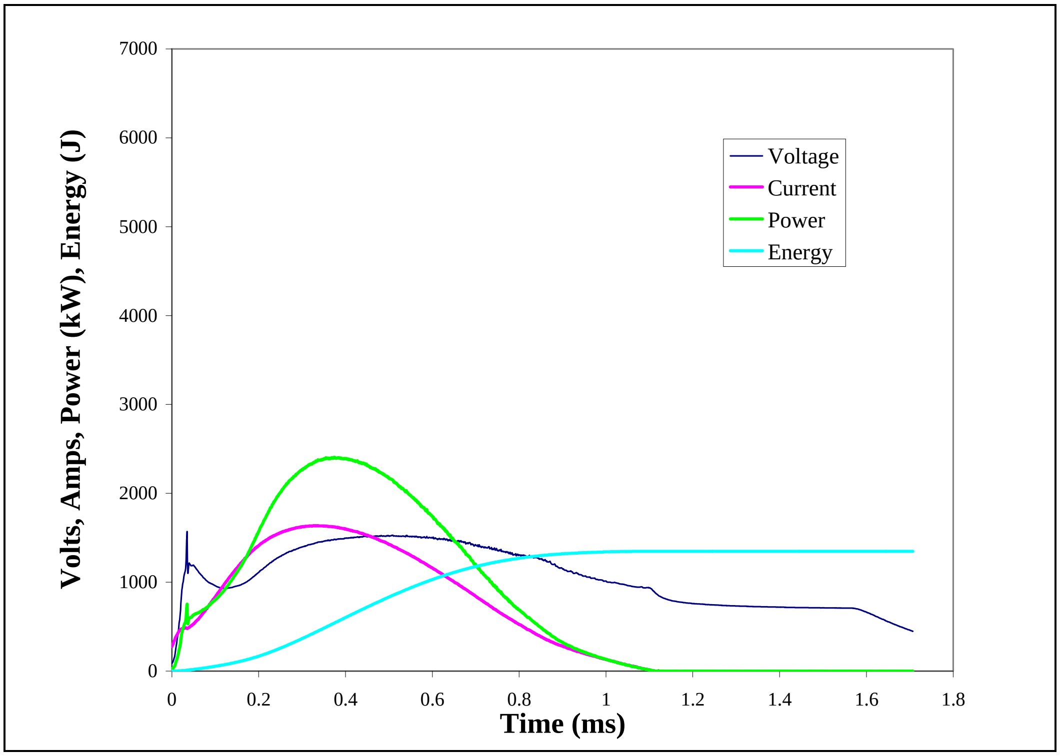

Figure 12. Electrical parameters measured for a live propellant shot with a pulse length of 1 ms.

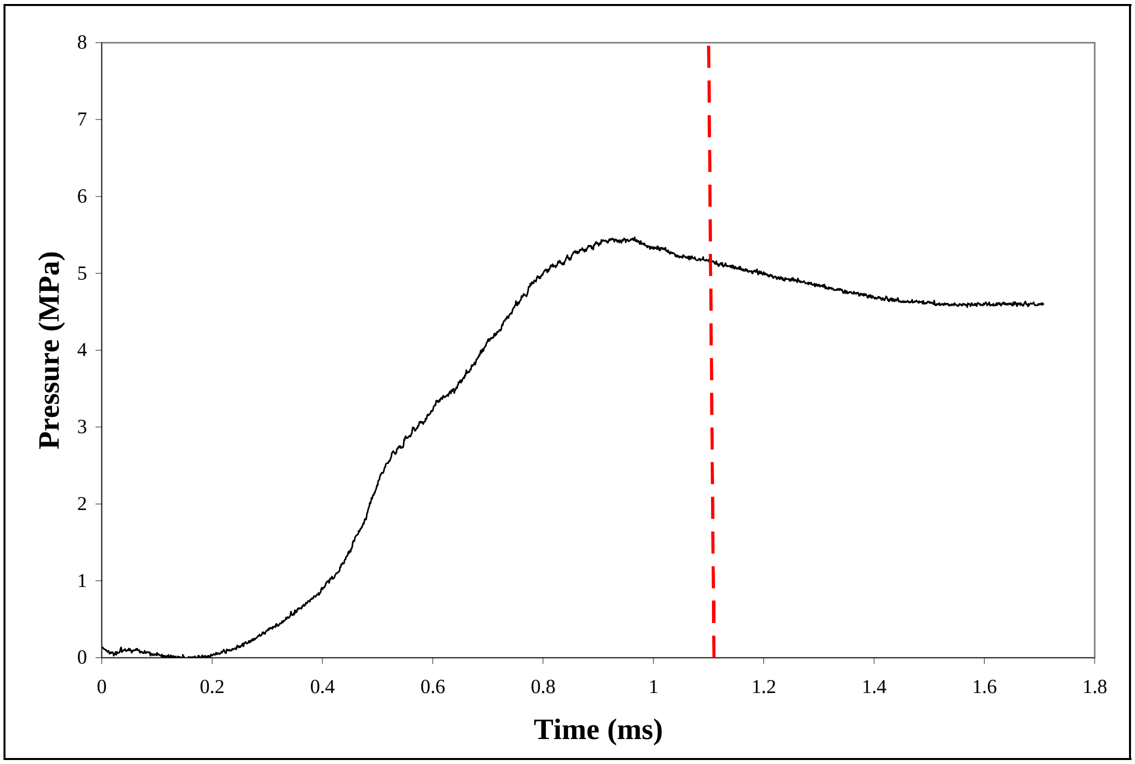

Figure 13. Pressure-time history at breech end for live-propellant shot in figure 12 (dashed line indicates end of electrical pulse).

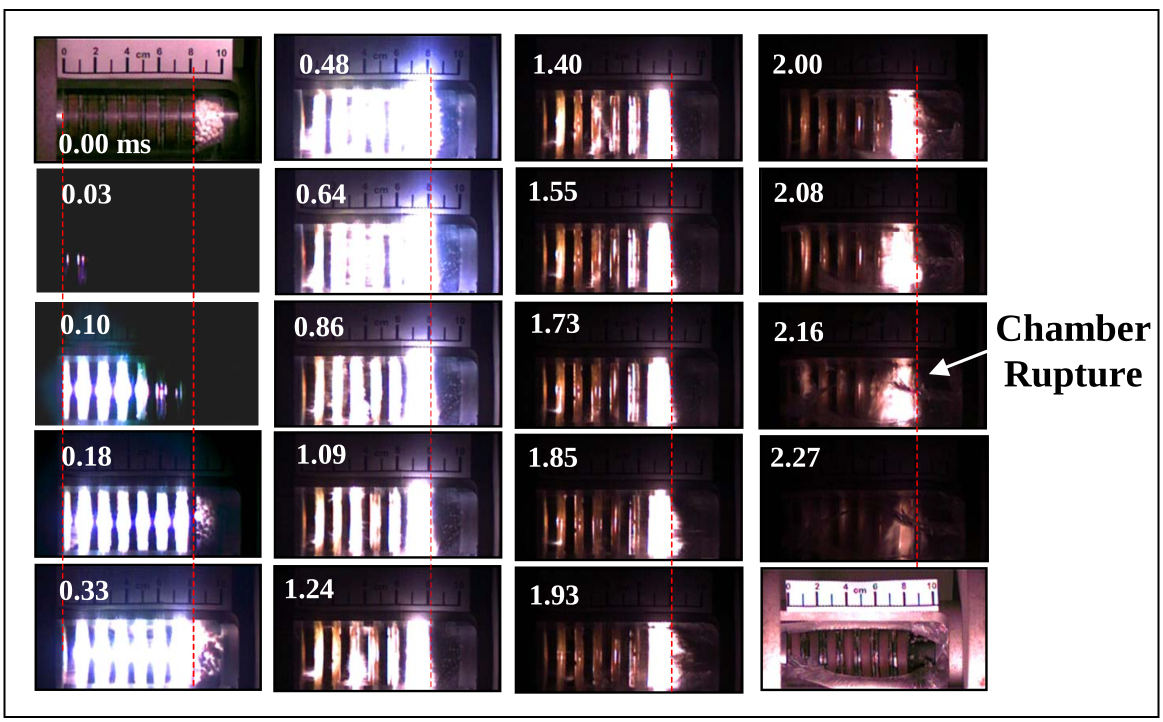

Figure 14. High-speed video of flamespread in a 25-mm live-JA2 propellant bed ignited with a pulse length of 1 ms (dashed line shows beginning of chambrage region).

plasma pulse were greater and were more sustained for the longer pulse. The pressure quickly diminished to about 2 MPa for the short pulse but only somewhat diminished to about 4.6 MPa for the long pulse until after 1.7 ms (the long pulse was executed after the short pulse so a longer data-acquisition time window was not anticipated since the short pulse had failed to sustain ignition).

In this test, ignition of the JA2 propellant obviously occurred by noting that the illuminated region was expanding toward the front end of the chamber at ~1.85 ms. In fact, the ignition of the propellant might have begun earlier. The illuminated region continued to expand until the chamber ruptured at around 2.2 ms, when the chamber pressure exceeded the strength of the chamber wall. Following the chamber rupture, depressurization occurred and the ignition/combustion of the propellant quenched immediately.

It is noted that, previously, a series of tests with a 30-mm granular charge system were conducted using plasma energy of 2.2 kJ as the ignition source (*22*). In these tests, faster sustained ignition/combustion of the charge was recorded for a pulse length of 0.3 ms than 0.9 ms. This seems to present a contradictive result to the current study. To explain the discrepancy, two areas are examined in the following: charge granulation and amount of plasma energy. The propellant bed of current interest consisted of a stack of discs individually separated by small gaps. After entering the central flow channel in the propellant bed, the plasma had to distribute its energy into those gaps. As the plasma flowed into the gaps, an increasing amount of propellant surface area would be exposed to the plasma. A continued supply of hot plasma would be required from the plasma generator to maintain the heating rate of the ever-increasing surface area so that ignition of the disc propellant would occur. Consequently, for the same ignition delay it would require more plasma energy to achieve sustained ignition/combustion of a disc-propellant charge than an aggregated propellant granular charge.

It was certainly possible that the plasma could quickly and locally ignite the corner parts (around the central flow channel) of the propellant discs. However, as stated earlier, the pyrolysis products from the corners could immediately be removed and blown into the cool regions in the down stream (i.e., the gap between propellant discs). This removal of the propellant pyrolysis products would make ignition/combustion unsustainable unless a large supply of plasma energy was available.

The amount of plasma energy released into the propellant bed is another variable to be considered. If much more energy than required is applied, plasma at a shorter pulse length may ignite the disc propellant charge quicker because of its higher energy intensity. However, the plasma energy available in a weapon system is constrained by limited size and weight of the power supply unit. Therefore, the ideal plasma energy should be kept to a level that is just sufficient to effectively ignite the charge. For this reason, plasma at a longer pulse length might be advantageous, at least, for the current disc-propellant charge. In comparison, there are vast differences in granulation and amount of plasma energy (1.1 kJ vs. 2.2 kJ) between the present

disc-propellant charge and the granular charge in the 30-mm system. The results suggest that the plasma pulse length is an important parameter to be optimized in designing an effective plasma ignition system.

4. Summary and Conclusion

Open-air plasma jet flows generated from an ablative capillary with different pulse lengths, 0.3 and 1 ms, were investigated and compared for their flow characteristics. For a given energy output, the 0.3-ms plasma pulse length resulted in a relatively wider flow field in front of the capillary as well as greater light intensity. However, with the 1-ms pulse length, the flow penetration in the air was much greater. Additionally, the action time of the flow, especially the duration of high-light-intensity, was significant longer.

The interaction of plasma flow with JA2 propellant in disc granulation in a closed 25-mm chamber was also investigated for the two pulse lengths. With 0.3-ms pulse length, the plasma flow in the propellant bed exhibited noticeably higher light intensity. However, the high-light-intensity period was shorter. Based on the pressure-time trace recorded, ignition/combustion of the propellant had occurred, but was not sustained. Without sustained ignition/combustion, the pressure rise in the chamber did not exceed the strength of the chamber wall, and thus the chamber remained intact. High-amplitude oscillations in pressure were present in the chamber. Apparently, they were induced by the complex interaction of plasma shock-wave flow with solid boundaries, such as propellant discs.

When the pulse length was extended to 1 ms, the results, including light intensity and plasma/propellant interaction time in the closed chamber, were noticeably different. Ignition of the propellant occurred and was sustained with the resultant pressure rise resulting in the rupture of the chamber.

These results suggest that plasma pulse length is an important parameter needed to be optimized in the design of a highly effective plasma ignition system with a minimum requirement of power supply.

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